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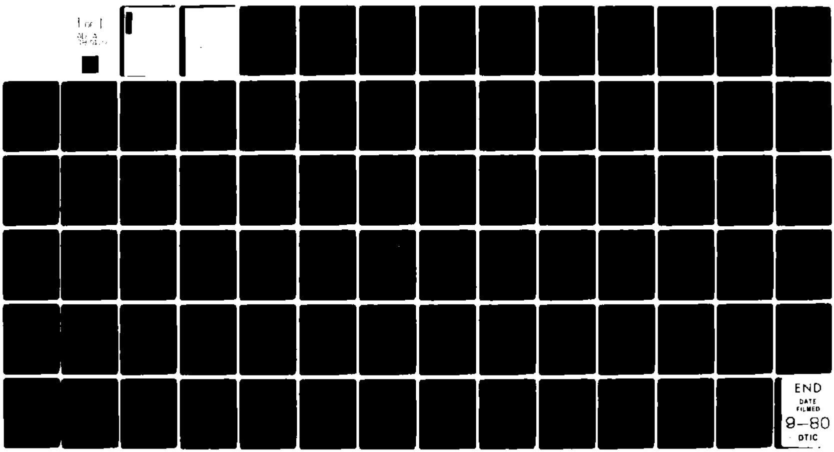

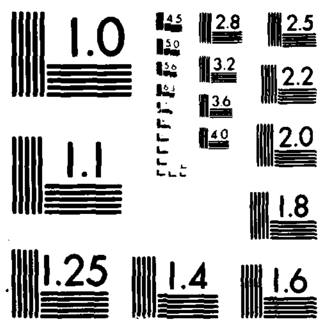

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WHERE ARE THE ASTEROIDS? THE DESIGN OF ASTPT AND ASTID

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ABSTRACT

This Note discusses the design of software to be used for the planning of minor planet observations and the identification of a particular asteroid when it is observed at a given time. In each case the large number of cataloged asteroids (~ 2200) has required that the software be optimal with respect to execution speed. This is accomplished by using an approximate geocentric ecliptic position to eliminate, as quickly (in terms of CPU time) as possible, the minor planet from further consideration. In particular, using the type of analysis applicable to near-stationary artificial satellites, (and carefully quantifying the nature of the approximations) an approximate geocentric ecliptic latitude and longitude are obtained in such a fashion that the computations needed for these are not only minimal but, should the actual location of the minor planet be needed, maximally used there too. The accuracy is (for $e \leq 0.3$, $i \leq 30°$) $3^{\circ}\!.9 \pm 2^{\circ}\!.1$ in geocentric ecliptic longitude and $3^{\circ}\!.5 \pm 1^{\circ}\!.8$ in geocentric ecliptic latitude. With these values we can eliminate approximately half of all asteroids because they will be on that half of the celestial sphere which corresponds to daytime. Half of the remainder are then eliminated because they will be below the observer's (usable, i.e., above altitude 30°) horizon. Here the asteroid's zenith

distance is computed in the ecliptic coordinate system. The user's interaction with the software, complete documentation of the calculations, a user's guide, sample outputs, and the rationale of observing asteroids are also discussed.

CONTENTS

I. INTRODUCTION

With the advent[1] of regular asteroid observing at the Experimental Test System (hereinafter ETS) of the Ground-based Electro-Optical Deep Space Surveillance (GEODSS) program* it became clear that a planning aid for routine observations and an identification aid for both routine observing and minor planet searches were necessary. The planning aid (whose acronym became ASTPT from ASTeroid PoinTing) would be a non-real time program similar to the one used at the ETS for scheduling the observations of artificial satellites[2]. The identification aid (ASTID) would be a program executed in real time. Since most asteroids are in essentially the same orbit (i.e., circular, in the plane of the ecliptic, 2.7 A.U. from the Sun) the identification space should be as large as possible. Hence provision to use position, angular velocity, apparent magnitude, color index, and lightcurve period would be necessary. Again there is a similar[3] real time program at the ETS but it only uses position†.

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*GEODSS will supplant the Baker-Nunn camera system.

†Angular velocity information and in and out of orbital plane information (relative to the supposed artificial satellite) is provided to the operator but not automatically used for discrimination purposes. The other data is unavailable for most high altitude artificial satellites at present.

The difficulty is the large size of the asteroid file - the current one contains 2188 entries and is rapidly growing[4]. The current GEODSS (essentially high altitude) artificial satellite file has 502 entries. Moreover, execution of the ETS correlation software frequently requires 20-25 seconds. Clearly something better in concept is needed.

This Note discusses the design of fast, efficient software which fulfills the requirements of the planning function. Execution, exclusive of the major output sections, only requires $\sim$ 63 seconds. Since only minor modifications are necessary to turn ASTPT into ASTID, and ASTID should execute at least $\sim$10 times faster than ASTPT does (cf. §VII), it would appear that the requirements of the real time identification function have also been met. A User's Guide to ASTPT is provided in the Appendix. Sample outputs are given in Figs. 1 and 2. Before turning to the details of the software, it is appropriate to review the reasons asteroids are observed at all at the ETS.

II. WHY WE OBSERVE ASTEROIDS

We observe asteroids because of their many similarities with (high altitude) artificial satellites and by regarding asteroids as "unknowns" we can thoroughly test many of our operating techniques, methods of data analysis and data reduction, initial orbit generation, and the differential correction of orbital elements. For instance asteroids are natural satellites of the Sun shining by reflected sunlight. Presumably all of them (there's detailed data on $\sim$ 350 lightcurves) spin about a fixed axis producing variations in their lightcurves which require analysis for the determination of (i) the sidereal rotation period, (ii) any precessional or nutational period that might be present, (iii) the orientation of the spin axis, (iv) the elimination of aspect variations and (v) size and shape determinations, and (vi) the elucidation of surface mottling[5]. Multicolor photometry (from reference 6, which is highly recommended as a general introduction and reference volume, we find that the mean B-V for the 744 asteroids with data is $0^{m}.77$ with a standard deviation about the mean of $0^{m}.09$) has proven useful for separating asteroids into classes based on chemical composition. Polarization data also aids in some studies and the combination of visible and infrared photometry (coupled with assumptions concerning albedo and emissivity) yields diameter estimates. Few asteroids are large enough or close enough to have a resolvable disc. Finally, in this category, analysis of minor planet phase functions may also yield surface compositions and an understanding of the opposition* effect - something akin to this having already been observed for artificial satellites[7].

The classical methods of obtaining positions of minor planets have already been successfully adopted for real time applications at the ETS (reference 8 contains an overview and complete references to supporting documentation; the current accuracy in the total positional error is $\approx 2''\!.5$). Minor planet orbits also exhibit strong perturbations due to third-body forces.

When we turn to searches we find two, modern, intensive, short-term efforts (the Yerkes-McDonald Survey[9] and the Palomar-Leiden Survey[10]). Longer term, less intensive efforts are principally performed at the Crimean Astrophysical Observatory[11] (with a 40 cm double astrograph) and by Helin and Shoemaker[12] for Earth-crossing asteroids (using the 18" Schmidt on Mount Palomar). The results and techniques of these efforts when coupled with our own searches for artificial satellites[13] and asteroids[1] should continue to improve the artificial satellite searches in several areas. Examples

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*The opposition effect refers to the abnormal brightening (by $\sim 0^{m}\!.4$) of an asteroid within a few ($\sim$ 8) degrees of opposition.

(and some successes) include a one telescope versus a coordinated two telescope search[13], dead-reckoning methods[13,14], and identification procedures[13]. It is in the field of initial orbit construction (e.g., the classical method of three positions versus statistical methods[15], methods based on preliminary distance estimation[16], or methods especially adapted to a particular orbital type[17]) that we expect the greatest dividends.

Clearly the interaction between the two sets of objects has already been fruitful and there is every indication that continuing to mine the store of asteroid observing, data reduction, and compiled information will further the goals of the GEODSS program. There are two other important points. Since no other observatory is as well equipped as the ETS is for performing the real time detection and discrimination of minor planets, or for obtaining their positions in real time, the telescope time is well spent <u>efficiently</u>. Clearly whatever data we do acquire will benefit the astronomical community. The other point is that <u>no</u> other observatory is capable of performing a real time search for asteroids. Here, especially for the increasingly important Earth-crossing objects, the ETS can play a unique role.

III. NOTATION

Since asteroids revolve about the Sun their orbital elements are clearly heliocentric - as are the locations derived from them. We, however, require geocentric (theoretically topocentric, see § VE) positions*. Furthermore the ecliptic of 1950.0 is the fundamental reference plane for the orbital element sets. Therefore, a variety of coordinates (rectangular, spherical; ecliptic, equatorial, and horizon; heliocentric, geocentric, and topocentric; 1950.0 epoch and epoch of date) are needed. In an attempt to have the notation imply as much information as possible the following scheme has been adopted: rectangular ecliptic coordinates will be denoted by x, y, z and spherical ecliptic coordinates by r, λ, β (distance, ecliptic or celestial longitude, and ecliptic or celestial latitude). Their interrelationship is given by

$$\underline{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = r \begin{pmatrix} \cos\beta\cos\lambda \\ \cos\beta\sin\lambda \\ \sin\beta \end{pmatrix} = r\underline{\ell}(\lambda,\beta)$$

Rectangular equatorial coordinates will be denoted by x, y, z and spherical equatorial coordinates by r, α, δ (the <u>same</u> distance for the <u>same</u> origin, right ascension, and declination).

*As is standard in astronomy position implies direction to a celestial object on the celestial sphere. Location is position plus distance.

Heliocentric coordinates are symbolized with lower case letters (as in r, α, δ or r, λ, β) and the corresponding geocentric quantities by upper case letters (e.g., R, A, Δ or R, Λ, B). Topocentric quantities and horizon system coordinates are, it turns out, unnecessary in practice except for the zenith distance Z (necessarily of date). Quantities relative to the 1950.0 ecliptic or relative to the mean equator and equinox of 1950.0 are denoted by a zero subscript (e.g., i_o, δ_o, Λ_o etc.). The same quantity relative to the mean ecliptic of date or relative to the mean equator and equinox of date has no subscript (e.g., i, δ, Λ). Distances are unaffected by general precession ($r = r_o$, $R = R_o$, etc.).

The parameters of the asteroid also have no subscript while those of the Sun carry $\odot$. Other important quantities include the asteroid's absolute B magnitude $B(1, 0)$, the phase angle f (the angle in the Sun-asteroid-Earth triangle with vertex at the asteroid), the local mean sidereal time τ, the observer's astronomical latitude ϕ, the coefficient of f in the phase function in magnitudes F, and the ecliptic longitude and latitude of the astronomical zenith (geocentric, epoch of date only) L_z, B_z.

This system of notation is rigidly adhered to for both our sakes. Thus, $\Lambda_\odot$ can only mean the geocentric, ecliptic longitude of the Sun relative to the mean equator and equinox of date. The principal symbols are defined below. When the same symbol has been used twice the most important meaning is given first.

a = semi-major axis of the asteroid orbit

a = general precession in longitude

$\underline{A}$ = see Eq. (7b); epoch of date

$\underline{A}_o$ = see Eq. (7b); epoch of 1950.0

$\underline{\acute{A}}$ = see Eq. (7a); epoch of date

$\underline{\acute{A}}_o$ = see Eq. (7a); epoch of 1950.0

$B(1,0)$ = absolute blue (B) magnitude of the asteroid

$B(rR,f)$ = apparent exo-atmospheric blue (B) magnitude of the asteroid; see Eq. (15)

B_z = geocentric latitude of the astronomical zenith, of date

e = eccentricity of the asteroid orbit

e_ℓ = lower eccentricity limit

e_u = upper eccentricity limit

E = eccentric anomaly; see Eq. (1)

f = phase angle; see Eq. (17) and Fig. 3

F = $0\overset{m}{.}023$/deg; see Eq. (15)

i = inclination of the asteroid orbit relative to the ecliptic, of date

i_o = inclination of the asteroid orbit relative to the ecliptic, 1950.0

i_ℓ = lower inclination limit

i_u = upper inclination limit

$\underline{\ell}(u,v) \equiv (\cos v \cos u, \cos v \sin u, \sin v)^T$

L_z = geocentric ecliptic longitude of the astronomical zenith, of date

m = speed of general precession in right ascension

m_b = lower apparent magnitude limit

m_f = upper apparent magnitude limit

m_{20} = apparent S-20 magnitude; see Eq. (19)

M = mean anomaly at time t

n = mean motion = $2\pi/a^{3/2}$

n = speed of general precession in declination

P = general precession matrix; see Eq. (13b)

q = aphelion distance of the asteroid = a(1 - e)

$r = r_o = \mathscr{r} = \mathscr{r}_o$ = heliocentric distance of the asteroid

$\underline{r} = r\underline{\ell}(\lambda,\beta) = (x,y,z)^T$ = heliocentric, ecliptic location of the asteroid, of date

$\underline{\mathscr{r}} = \mathscr{r}\underline{\ell}(\alpha,\delta) = (\mathscr{x},\mathscr{y},\mathscr{z})^T$ = heliocentric, equatorial location of the asteroid, of date

$\underline{r}_o = r\underline{\ell}(\lambda_o,\beta_o) = (x_o,y_o,z_o)^T$ = heliocentric, ecliptic location of the asteroid, 1950.0

$\underline{\mathit{r}}_o = \mathit{r}\underline{\ell}(\alpha_o,\delta_o) = (\mathit{x}_o,\mathit{y}_o,\mathit{z}_o)^T$ = heliocentric, equatorial location of the asteroid, 1950.0

$R = R_o = \mathcal{R} = \mathcal{R}_o$ = geocentric distance of the asteroid

$\underline{R} = R\underline{\ell}(\Lambda,B) = (X,Y,Z)^T$ = geocentric, ecliptic location of the asteroid, of date

$\underline{\mathcal{R}} = \mathcal{R}\underline{\ell}(A,\Delta) = (\mathcal{X},\mathcal{Y},\mathcal{Z})^T$ = geocentric, equatorial location of the asteroid, of date

$\underline{R}_o = R\underline{\ell}(\Lambda_o,B_o) = (X_o,Y_o,Z_o)^T$ = geocentric, ecliptic location of the asteroid, 1950.0

$\underline{\mathcal{R}}_o = \mathcal{R}\underline{\ell}(A_o,\Delta_o) = (\mathcal{X}_o,\mathcal{Y}_o,\mathcal{Z}_o)^T$ = geocentric, equatorial location of the asteroid, 1950.0

$R_\odot$ = geocentric distance of the Sun

$\underline{R}_\odot = R_\odot\underline{\ell}(\Lambda_\odot,B_\odot)$ = geocentric, ecliptic location of the Sun, of date

$\underline{\mathcal{R}}_\odot = \mathcal{R}_\odot\underline{\ell}(A_\odot,\Delta_\odot)$ = geocentric equatorial location of the Sun, of date

$$R_1(u) = x\text{ - axis rotation matrix by angle } u = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos u & \sin u \\ 0 & -\sin u & \cos u \end{pmatrix}$$

$$R_2(v) = y\text{ - axis rotation matrix by angle } v = \begin{pmatrix} \cos v & 0 & -\sin v \\ 0 & 1 & 0 \\ \sin v & 0 & \cos v \end{pmatrix}$$

$$R_3(w) = z - \text{axis rotation matrix by angle } w = \begin{pmatrix} \cos w & \sin w & 0 \\ -\sin w & \cos w & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$S = R_3(-\Omega_o)R_1(-i_o)R_3(-\omega_o)$; see Eqs. (5)

t = the time of interest

T = the time of perihelion passage of the asteroid

$u = v + \omega$ = true argument of latitude, of date

$u_o = v + \omega_o$ = true argument of latitude, 1950.0

v = true anomaly, see Eq. (3)

z = equatorial precession quantity, see Eq. (13c)

Z = zenith distance of asteroid

α = heliocentric right ascension of the asteroid, of date

α_o = heliocentric right ascension of the asteroid, 1950.0

A = geocentric right ascension of the asteroid, of date

A_o = geocentric right ascension of the asteroid, 1950.0

$A_\odot$ = geocentric right ascension of the Sun, of date

β = heliocentric ecliptic latitude of the asteroid, of date

β_o = heliocentric ecliptic latitude of the asteroid, 1950.0

B = geocentric ecliptic latitude of the asteroid, of date

B_o = geocentric ecliptic latitude of the asteroid, 1950.0

$B_\odot$ = geocentric ecliptic latitude of the Sun, of date

γ = see Eq. (21c)

δ = heliocentric declination of the asteroid, of date

δ_o = heliocentric declination of the asteroid, 1950.0

Δ = geocentric declination of the asteroid, of date

Δ_o = geocentric declination of the asteroid, 1950.0

$\Delta_\odot$ = geocentric declination of the Sun, of date

$\Delta\varepsilon$ = nutation in obliquity

$\Delta\psi$ = nutation in longitude

ε = obliquity of ecliptic, of date

ε_o = obliquity of ecliptic, 1950.0

ζ_o = equatorial precession quantity, see Eq. (13c)

θ = equatorial precession quantity, see Eq. (13c)

λ = heliocentric ecliptic longitude of the asteroid, of date

λ_o = heliocentric ecliptic longitude of the asteroid, 1950.0

Λ = geocentric ecliptic longitude of the asteroid, of date

Λ_o = geocentric ecliptic longitude of the asteroid, 1950.0

$\Lambda_\odot$ = geocentric ecliptic longitude of the Sun, of date

$\underline{\rho}$ = see Eq. (2)

τ = local mean sidereal time

ϕ = astronomical latitude of the observer

ω = argument of perihelion of the asteroid relative to the ecliptic of date

ω_o = argument of perihelion of the asteroid relative to the ecliptic 1950.0

Ω = longitude of ascending node of the asteroid relative to the ecliptic of date

Ω_o = longitude of ascending node of the asteroid relative to the ecliptic of 1950.0

IV. THE USER'S INTERACTION

A. Inputs

While designing the input/output sections of ASTPT, which will primarily be used to prepare observing schedules, the objectives of observing asteroids (§II) at all have been the principal consideration. Thus the operator can select apparent magnitude, inclination, and eccentricity ranges and the order of presentation of the data. For example one might only want to use high eccentricity ($e \gtrsim 0.23$) or high inclination ($i \gtrsim 14°$) asteroids to test dead-reckoning or initial orbit determination schemes. To mimic a search for near-stationary artificial satellites the desirable minor planets would have low eccentricity ($e \lesssim 0.23$) and low inclination ($i \lesssim 14°$), and the output should be arranged in order of right ascension. Testing the efficacy of actual operations would benefit from an angular speed sort. Multi-color photometric data acquisition and analysis and light curve analysis would benefit from both apparent magnitude selection and sorting of the output by brightness. Similarly the delineation of magnitude effects near the limits of detection and discrimination would benefit from these options. Therefore, the user is asked to specify six parameters relating to apparent magnitude, inclination, and eccentricity or accept their default values. The parameters are

m_b = the lower (bright) limit for the apparent magnitude

m_f = the upper (faint) limit for the apparent magnitude

i_ℓ = the lower limit for the inclination

i_u = the upper limit for the inclination

e_ℓ = the lower limit for the eccentricity

e_u = the upper limit for the eccentricity

The default values are $m_b = 0^m$, $m_f = 18^m.5$; $i_\ell = 0°$, $i_u = 180°$; $e_\ell = 0$, $e_u = 1$. The bright limit is arbitrary and insures that no minor planet will be arbitrarily excluded. The faint limit represents the experimentally determined[1] ETS limit for positive detection and discrimination. Through a question and answer phase of ASTPT the user can alter any subset of these six quantities. Illegal entries (e.g., $m_b \geq m_f$, $i_\ell \geq i_u$, $e_\ell \geq e_u$; m_b or $m_f \geq 18^m.5$, i_ℓ or $i_u > 180°$, e_ℓ or $e_u > 1$; $e_\ell < 0$, $i_\ell < 0$) are prevented.

Of course, the user must also supply the program with the date of interest. The year is assumed to be the current one and the month and day of the month are the necessary inputs. Specification of the exact time of interest is not necessary because the program automatically produces positions for (local mean solar times) 6 P.M., 12 A.M., and 6 A.M. That is, if the user requests output for (say) Feb. 5 he will receive data for 6 P.M. Feb. 5, 12 A.M. Feb. 6, and 6 A.M.

Feb. 6. If he insists on interpolating* he can do so. Illegal entries are prevented here too.

After fixing the date and making his choice of the apparent magnitude, inclination, and eccentricity limits the user must supply the number of the tape drive unit that the master asteroid tape file has been mounted on. For this and all other operator requested input the program immediately provides an echo print and allows the operator to immediately modify his input. Moreover the user, after entering the month and day of the month, has the option of dealing with m_b, m_f; i_ℓ, i_u; e_ℓ, e_u; tape drive unit one group at a time or all of them simultaneously. If he chooses all at once and fails to respond properly he can still return to the one group at a time mode.

Each cataloged asteroid is assigned a unique identification number. Our file (kindly supplied in machine readable form by Prof. Brian Marsden, Director of the Minor Planet Center) contains 2188 entries ordered according to increasing identification number. This is also the standard format for all compilations of asteroid data. Output is most easily provided in this sequence and represents the default option of ASTPT. Even if other sequences are desired this listing will be

*A fast moving main belt minor planet would have a geocentric angular speed of 1'/hr.

provided. As discussed above other sequences of interest are increasing right ascension, geocentric angular speed, or apparent magnitude. After specifying the tape drive unit the user can request no additional sorting, any single sort, or any combination of multiple sorts (performed and listed separately; the possibility of an angular speed sort within a right ascension sort may be added). Sorted data is indicated by the heading (see Figs. 1 and 2), not by rearranging the output format to forcefully reflect the fact that a sort had been performed.

Sample sessions of interaction with the program are in the Appendix. This includes error messages too. There is <u>no</u> way of automatically choosing by default the default values for the above parameters.

B. Outputs

The form and content of the output, given the flexibility already provided to the user, has been designed to minimize computation (in his head and the CPU) and maximize usefulness. Our earlier experience with a more primitive version[1] of this type of software has led to the format shown in Fig. 1. For each visible* minor planet three lines are given. The top line has the geocentric right ascension and declination (both in

*An asteroid is "visible" if and only if it passes all apparent magnitude, inclination, and eccentricity criteria and is above altitude = 30° at midnight.

sexagesimal measure, time and circular respectively, to the nearest second*) for the mean equator and equinox of midnight (hereinafter the mean equator and equinox of date, see §§VB,VIA, VIB) at the instant of time corresponding to 6 P.M. The effects of planetary perturbations have been ignored, the effects of parallax [(heliocentric-geocentric only; not diurnal (see §VE)] and planetary aberration (§ VD) are included. The second line contains identification number, apparent S-20 magnitude† (including the effects of heliocentric and geocentric distance, phase, atmospheric extinction, color corrections from B, and the opposition effect; see §VD), A and Δ (as on the top line) for the instant of time corresponding to 12 A.M., the time needed for the asteroid to move 7".5 in minutes of time to the nearest minute (which experience at the ETS has shown to be the minimum distance for efficient, positive detection and discrimination), the position angle (in degrees to the nearest 10°) of the geocentric angular velocity, the compass direction (i.e., NE or S) of the angular velocity to the nearest 22°.5, and a flag (an asterisk)

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*I realize that this is inconsistent. It's also superfluous (see §§VA, VIA) but it is the standard input format for moving the telescope to a particular position at the ETS.

†The photo-sensitive surface of the ETS cameras is an S-20 type.

indicating eastward motion (if appropriate)*. The last line gives A and Δ (as on the top line) for 6 A.M.

Flags for high eccentricity or high inclination were deemed unnecessary. Anyway this is rare. From reference 18, for a sample of 2829† asteroids, we find that the average eccentricity in the asteroid belt is 0.153 with a standard deviation about the mean of 0.079 and that the average inclination in the asteroid belt is 7°93 with a standard deviation about the mean of 5°74. Hence, the one-sigma upper limits (the 0.23 and 14° mentioned above) are accidently comparable to those in the definition[17] of a near-stationary artificial satellite. Of these 2829 minor planets only 10 had inclinations in excess of 30° and only 45 had eccentricities in excess of 0.3. Moreover, high inclination and high eccentricity seem to go together‡.

Figure 2 shows a portion of a right ascension sort. All sorts are based on midnight values of the relevant parameter(s).

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*Eastward moving asteroids are in their retrograde loop and present some initial orbit and dead reckoning problems not faced when observing artificial satellites.

†This sample consisted of a union of the (then -1969) numbered asteroids and the "first-class" orbits from the Palomar-Leiden Survey[18].

‡Seventeen minor planets with $e \geq 0.3$ also have $i \geq 22°$.

THIS IS FOR 6 8 80 AT 6 PM, 12 AM, AND 6 AM LOCAL TIME

MB= 12.5 MF= 18.5 IL= 5.0 IU= 90.0 EL= 0.1 EU= 0.5

THIS SORT IS BY ID NUMBER PAGE 5 OF 8

ID NUMBER	S-20 MAG	RA HH MM SS	DEC DD MM SS	TIME TO MOVE	POS ANGLE	DIREC-TION	
		16 19 18	-9 24 41				
1033	17.1	16 19 22	-9 25 32	36	130	SE	*
		16 19 25	-9 26 24				
		17 12 15	-8 17 38				
1094	17.2	17 12 15	-8 19 17	27	180	S	*
		17 12 15	-8 20 56				
		16 7 43	-7 33 51				
1102	15.4	16 7 49	-7 34 30	27	110	E	*
		16 7 55	-7 35 8				
		16 59 38	-5 56 17				
1139	17.5	16 59 39	-5 57 24	39	170	S	*
		16 59 40	-5 58 31				
		15 17 59	-7 20 16				
1165	15.8	15 18 11	-7 21 20	14	110	E	*
		15 18 23	-7 22 24				
		14 52 55	-25 42 55				
1226	17.5	14 53 10	-25 43 39	13	100	E	*
		14 53 26	-25 44 23				
		17 7 36	-11 2 39				
1276	17.1	17 7 37	-11 4 20	26	190	S	
		17 7 38	-11 6 1				
		14 58 23	-14 11 46				
1294	17.0	14 58 31	-14 12 56	19	120	SE	*
		14 58 40	-14 14 6				
		12 53 42	16 24 52				
1301	16.6	12 54 3	16 22 54	8	110	E	*
		12 54 24	16 20 56				
		11 51 33	-5 22 53				
1310	17.2	11 51 56	-5 26 8	7	120	SE	*
		11 52 18	-5 29 23				
		15 1 24	-2 36 0				
1329	15.1	15 1 40	-2 39 0	9	130	SE	*
		15 1 55	-2 42 0				
		15 57 4	-18 48 43				
1357	15.8	15 57 8	-18 49 42	32	130	SE	*
		15 57 13	-18 50 41				
		13 47 22	12 57 32				
1362	17.9	13 47 30	12 55 40	16	130	SE	*
		13 47 39	12 53 47				

Fig. 1. One page of ASTP output sorted according to increasing asteroid identification number.

THIS IS RUN 9 8 80 AT 6 PM, 12 AM, AND 6 AM LOCAL TIME

MB= 12.5 MF= 18.5 IL= 5.0 IU= 90.0 EL= 0.1 EU= 0.5

THIS SORT IS BY RIGHT ASCENSION PAGE 4 OF 8

ID NUMBER	S-20 MAG	RA HH	RA MM	RA SS	DEC DD	DEC MM	DEC SS	TIME TO MOVE	POS ANGLE	DIRECTION	
		14	57	0	-21	4	2				
769	14.7	14	57	12	-21	5	1	14	110	E	*
		14	57	25	-21	6	1				
		14	57	24	-8	43	47				
909	16.8	14	57	39	-8	45	40	11	120	SE	*
		14	57	55	-8	47	33				
		14	58	23	-14	11	46				
1294	17.0	14	58	31	-14	12	56	19	120	SE	*
		14	58	40	-14	14	6				
		15	0	5	-22	53	47				
428	17.1	15	0	18	-22	54	23	15	100	E	*
		15	0	30	-22	54	59				
		15	1	24	-2	36	0				
1329	15.1	15	1	40	-2	39	0	9	130	SE	*
		15	1	55	-2	42	0				
		15	4	41	-11	52	8				
1011	17.9	15	4	55	-11	53	42	12	120	SE	*
		15	5	8	-11	55	15				
		15	5	12	-13	45	19				
102	14.7	15	5	23	-13	46	7	16	110	E	*
		15	5	34	-13	46	56				
		15	6	1	-21	52	39				
910	15.2	15	6	16	-21	53	59	12	110	E	*
		15	6	31	-21	55	19				
		15	6	33	-1	20	29				
1022	15.0	15	6	48	-1	24	18	8	130	SE	*
		15	7	3	-1	28	7				
		15	9	10	-9	55	28				
771	16.8	15	9	18	-9	56	3	21	110	E	*
		15	9	27	-9	56	38				
		15	9	58	-26	3	32				
2040	16.0	15	10	6	-26	4	3	23	110	E	*
		15	10	15	-26	4	34				
		15	11	32	-21	23	37				
1889	17.0	15	11	41	-21	24	34	20	110	SE	*
		15	11	50	-21	25	31				
		15	12	0	-25	31	12				
757	15.7	15	12	13	-25	31	39	16	100	E	*
		15	12	25	-25	32	7				

Fig. 2. One page of ASTP output sorted according to right ascension at midnight.

V. THE COMPUTATIONS

Some of the computations involved are not executed in the rigorous fashion. In this Section the rigorous (or very nearly rigorous) procedures are described. As this is fairly complicated (because of the general precession-parallax interplay and the number of quantities we must calculate) the approximations are documented in §VI.

A. Heliocentric Locations

The osculating orbital element set for epoch 1950.0 in the classical form (e.g., a, e, i_o, ω_o, Ω_o, and T) is the starting point. The common date of osculation is 0^h Dec. 27, 1980 E.T. As these are not perfect and planetary perturbations are ignored I expect a positional accuracy of 1' within a year or two of the date of osculation. This is small enough to satisfy both the planning* and identification† requirements. To obtain the rectangular, ecliptic, heliocentric coordinates for the equator and equinox of 1950.0 ($\underline{r}_o$) we first determine the mean anomaly M from

$$M = n(t - T), \qquad n = 2\pi/a^{3/2}$$

*The field of view of the 31" telescope at the ETS when electronically zoomed in the Cassegrain configuration is ∿ 20'.

†If we view the asteroid belt as occupying 30° of ecliptic latitude, then the mean density of cataloged minor planets is 0.2/sq degree. Hence, their mean separation is 1°25 and the probability of two being within 2' of each other, given that one is already there, is 0.07%.

where a is in A.U., n in rad/yr, and with t (the time of interest, i.e., 6 P.M. Feb. 5, 1980 local mean solar time) and T being measured in years of ephemeris time measure. This requires that the difference between Universal Time and Ephemeris Time be known. This is the case, in advance, to $\sim 0\overset{s}{.}2$. Again using 1"/min as representative of a fast main belt asteroid (=> a = 1.8 A.U. for a circular orbit) the resultant error is negligible.

Next we solve Kepler's equation for the eccentric anomaly E,

$$E - e\sin E = M \qquad (1)$$

and obtain the vector

$$\underline{\rho} = a \begin{pmatrix} \cos E - e \\ \sqrt{1 - e^2}\sin E \\ 0 \end{pmatrix} \qquad (2)$$

The computation of the true anomaly v and the heliocentric distance r is unnecessary;

$$\tan(v/2) = [(1 + e)/(1 - e)]^{1/2}\tan(E/2) \qquad (3)$$

$$r = a(1 - e\cos E) \qquad (4)$$

Finally we perform the rotations to correct for non-zero values of ω_o, Ω_o, and i_o,

$$\underline{r}_0 = S\underline{\rho} \tag{5a}$$

where

$$S = R_3(-\Omega_0)R_1(-i_0)R_3(-\omega_0) \tag{5b}$$

To obtain rectangular, equatorial, heliocentric coordinates for the equator and equinox of 1950.0 ($\underline{\mathscr{r}}_0$) we need an additional rotation by the obliquity of the ecliptic,

$$\underline{\mathscr{r}}_0 = R_1(-\varepsilon_0)\underline{r}_0; \qquad \varepsilon_0 = 23^\circ 26' 44''.836 \tag{6}$$

There is a very old trick in astronomy to simplify the application of Eqs. (5,6). Define vectors $\underline{\mathcal{A}}_0$, $\underline{\mathcal{B}}_0$ and $\underline{A}_0$, $\underline{B}_0$ by (with $Su = \sin u$, $Cu = \cos u$ $\forall u$ to save space)

$$\underline{\mathcal{A}}_0 = a \begin{pmatrix} C\omega_0 C\Omega_0 - S\omega_0 S\Omega_0 Ci_0 \\ (C\omega_0 S\Omega_0 + S\omega_0 C\Omega_0 Ci_0)C\varepsilon_0 - S\omega_0 Si_0 S\varepsilon_0 \\ (C\omega_0 S\Omega_0 + S\omega_0 C\Omega_0 Ci_0)S\varepsilon_0 + S\omega_0 Si_0 C\varepsilon_0 \end{pmatrix}$$

$$\underline{\mathcal{B}}_0 = a(1 - e^2)^{1/2} \begin{pmatrix} -S\omega_0 C\Omega_0 - C\omega_0 S\Omega_0 Ci_0 \\ (-S\omega_0 S\Omega_0 + C\omega_0 C\Omega_0 Ci_0)C\varepsilon_0 - C\omega_0 Si_0 S\varepsilon_0 \\ (-S\omega_0 S\Omega_0 + C\omega_0 C\Omega_0 Ci_0)S\varepsilon_0 + C\omega_0 Si_0 C\varepsilon_0 \end{pmatrix} \tag{7a}$$

$$\underline{A}_0 = \underline{\mathcal{A}}_0\Big|_{\varepsilon_0 = 0}, \qquad \underline{B}_0 = \underline{\mathcal{B}}_0\Big|_{\varepsilon_0 = 0} \tag{7b}$$

Then,

$$\underline{r}_0 = (x_0, y_0, z_0)^T = (CE - e)\underline{A}_0 + (SE)\underline{B}_0 \tag{8}$$

$$\underset{\sim}{r}_o = (x_o, y_o, z_o)^T = (CE - e)\underset{\sim}{A}_o + (SE)\underset{\sim}{B}_o$$

As it's $\underset{\sim}{r}_o$ we want, and $\underset{\sim}{A}_o$ and $\underset{\sim}{B}_o$ can be stored on the master asteroid tape, Eq. (8) represents an efficient method of obtaining $\underset{\sim}{r}_o$.

B. General Precession and Parallax

If you introduce an intermediate epoch ("in between" the fundamental epoch of 1950.0 and the epoch of date; you'll see why, and why in between is in quotes, in a minute) to perform the general precession calculation and start to enumerate all the possibilities (rectangular versus spherical; ecliptic versus equatorial) you'll very rapidly wind up with a long list because it's the precessed <u>geocentric</u> location we want. It turns out that equatorial is better than ecliptic (the reasons aren't given here) and that rectangular is much better than spherical (no expensive trigonometric functions and their equally expensive inverses to perform). Even so, since we could've precessed ω_o, Ω_o, and i_o there are still five different methods of handling the interplay between general precession and the heliocentric-geocentric parallax.

1. We could precess ω_o, Ω_o, and i_o to the epoch of date*, compute $\underset{\sim}{r}$ and then add $\underset{\sim}{R}_\odot$ to form $\underset{\sim}{R}$ (see Fig. 3). Since we

*These formulas are complicated and can be found on pages 273-275 of reference 19.

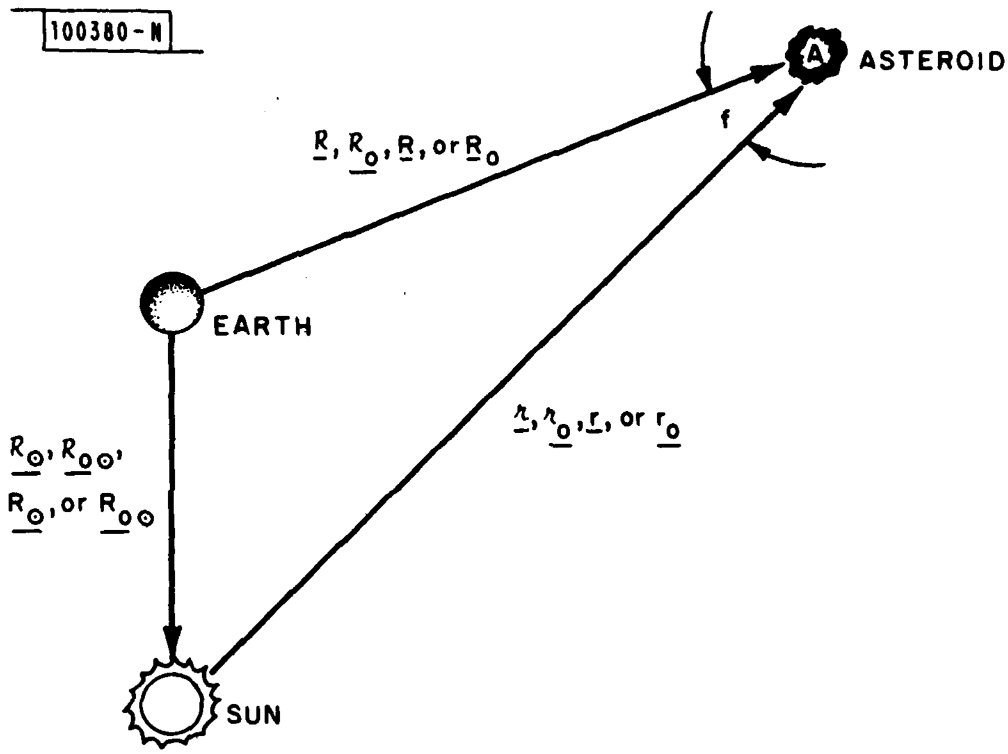

Fig. 3. The Earth ($\oplus$), Sun ($\odot$), and asteroid (Ⓐ). Note that $\underline{\mathcal{R}} = \underline{\mathcal{R}_\odot} + \underline{\imath}$, $\underline{\mathcal{R}_o} = \underline{\mathcal{R}_{o\odot}} + \underline{\imath_o}$, $\underline{R} = \underline{R_\odot} + \underline{r}$, and $\underline{R_o} = \underline{R_{o\odot}} + \underline{r_o}$. The phase angle is f.

don't know the epoch of date all of the trigonometric computations implicit in Eqs. (5 and 6) have to be performed within ASTPT. Therefore this possibility is rejected. For reference, the approximate (second-order) formulas to do this (my advice is to go to possibility #2) are

$$\begin{aligned} \Omega &= \Omega_o + a - b\sin(\Omega_o + c)\cot i \\ \omega &= \omega_o + b\sin(\Omega_o + c)\csc i \\ i &= i_o + b\cos(\Omega_o + c) \end{aligned} \tag{9}$$

where a is the general precession in longitude, b is the inclination of the ecliptic of date to that of 1950.0, and c = 180° - Π + a/2 where Π is the ascending node of the ecliptic of date on the 1950.0 ecliptic referred to the mean equator and equinox of date. This notation is standard. Numerical values for a and b are

$$a = p(t - 1950.0), \qquad b = \pi(t - 1950.0)$$

where p is the speed of the general precession in longitude and π is the rate of rotation of the ecliptic (both per year here). Their approximate values, and values of comparable accuracy for Π and ε, are

$$p = (50''.256 + 0''.0222T)/yr$$

$$\pi = (0''.471 - 0''.0007T)/yr$$

$$\Pi = 173°57'.06 + 54'.77T$$

$$\varepsilon = 23°27'08''.26 - 46''.845T$$

where T is the time since 1900.0 in tropical centuries. To keep Eqs. (9) second-order T should be (t + 1950.0)/2.

2. Precess ω_o, Ω_o, and i_o to 1980.0 (for calendar year 1980 pointing) and store these as $\underline{A}'$ and $\underline{B}'$ on the master asteroid tape. Now only (my notation scheme is running into trouble)

$$\underline{r}' = (\cos E - e)\underline{A}' + (\sin E)\underline{B}' \tag{10}$$

is executed in ASTPT. Add to this $\underline{R}'_{\odot}$ to form $\underline{R}'$. We then obtain $\underline{R}$ by precessing from 1980.0 to the mean equator and equinox of date. Since this time interval is short we can do this, with adequate accuracy, via

$$\underline{\ell}(A, \Delta) = \underline{\ell}(A', \Delta') + d\underline{\ell}(A', \Delta')/dt \bullet \Delta t \tag{11}$$

where, if $\underline{\ell}(A', \Delta') = (\xi,\eta,\zeta)^T$, then

$$d\underline{\ell}/dt = \begin{pmatrix} -n\zeta - m\eta \\ m\xi \\ n\xi \end{pmatrix} \tag{12}$$

and m and n are the speeds of general precession in right ascension and declination,

$$m \simeq (46''.085 + 0''.0279T)/yr$$

$$n \simeq (20''.047 - 0''.0085T)/yr$$

T is again the time in tropical centuries since 1900.0 [(t + 1980.0)/2 here] and Δt in Eq. (11) is t - 1980.0. This method is as efficient as possibility #3 and these are the two most efficient of the five possibilities considered here. The difficulty is that $\underline{R}'$ is not easily available.

3. What is available is $\underline{R}'$ from Jan. 1, 1980 to Jul. 1, 1980 relative to the mean equator and equinox of 1980.0 and $\underline{R}'$ relative to the mean equator and equinox of 1981.0 for Jul. 1, 1980 to Dec. 31, 1980 (remember for 1980 read any year). Hence, if we separate the year into two parts, store ω, Ω, and i in the $\underline{A}'$, $\underline{B}'$ format on our tape for both 1980.0 and 1981.0, then we can use the technique of possibility #2. But, when I say that $\underline{R}'$ is available it is so only in tabular (but machine readable) form. For now I preferred a simple analytic expression for $\underline{R}'$ or $\underline{R}$ even at the loss of some precision.

4. If we invert the logic of possibilities 2 and 3 we proceed via Eq. (8) for $\underline{r}_o$, then add $\underline{R}_{o\odot}$ (only available in [machine readable] tabular form) to obtain $\underline{R}_o$ and precess via

$$\underline{R} = P\underline{R}_o \tag{13a}$$

The matrix P is given by

$$P = R_3(-z)R_2(\theta)R_3(-\zeta_o) = R_3(-z-90°)R_1(\theta)R_3(90°-\zeta_o) \tag{13b}$$

where ζ_o, z, and θ are the equatorial precessional quantities;

$$\begin{aligned} \zeta_o &= 2304''.95177\Delta t + 0''.30217(\Delta t)^2 + 0''.01800(\Delta t)^3 \\ z &= \zeta_o + 0''.79303(\Delta t)^2 + 0''.00032(\Delta t)^3 \\ \theta &= 2004''.25826\Delta t - 0''.42689(\Delta t)^2 - 0''.04180(\Delta t)^3 \end{aligned} \tag{13c}$$

where Δt is now (t - 1950.0)/100 and the initial epoch dependence of the equatorial precessional quantities (i.e., 1950.0) is implicitly included in the above formulas. While P requires six trigonometric evaluations and many multiplications and additions for its formation this is overhead in the sense that P is formed once per ASTPT execution and not once per minor planet. It was the tabular source for $\underline{R}_{o\odot}$ that ruled this possibility out plus its relative inefficiency compared to #2 or #3.

5. Finally, since an excellent, simple, analytical form is available[20] for $\underline{R}_\odot$ the procedure used is (i) obtain $\underline{r}_o$ by Eq. (8), (ii) precess to the epoch of date by Eqs. (13) to obtain $\underline{r} = P\underline{r}_o$, and (iii) then add $\underline{R}_\odot$ which yields $\underline{R}$.

C. The Location of the Sun

The Almanac for Computers[20] provides Chebyshev expansions for the geocentric right ascension, declination, and distance of the Sun relative to the true equator and equinox of date.

It also provides similar series for the nutation in longitude $\Delta\psi$ and the nutation in obliquity $\Delta\varepsilon$. Accuracy to $0\overset{s}{.}6$, $3''$, 4×10^{-5} AU, $0\overset{''}{.}4$, and $0\overset{''}{.}2$ respectively is available. A subroutine (called SUN) exists in ASTPT which computes these values and then corrects the geocentric right ascension and declination relative to the true equator and equinox of date (say $A''_\odot$, $\Delta''_\odot$) to the geocentric right ascension and declination relative to the mean equator and equinox of date ($A_\odot$, $\Delta_\odot$) by

$$A_\odot = A''_\odot - (\cos\varepsilon'' + \sin\varepsilon''\sin A''_\odot\tan\Delta''_\odot)\Delta\psi + (\cos A''_\odot\tan\Delta''_\odot)\Delta\varepsilon$$

$$\Delta_\odot = \Delta''_\odot - (\sin\varepsilon''\cos A''_\odot)\Delta\psi - (\sin A''_\odot)\Delta\varepsilon$$

where $\varepsilon'' = \varepsilon + \Delta\varepsilon$ is the true obliquity of date. From $\underline{R}_\odot = R_\odot\underline{\ell}(A_\odot, \Delta_\odot)$ the spherical, ecliptic, geocentric coordinates for the Sun, relative to the mean equator and equinox of date are computed by

$$\underline{\ell}(\Lambda_\odot, B_\odot) = \begin{pmatrix} \cos\Delta_\odot\cos A_\odot \\ \cos\Delta_\odot\sin A_\odot\cos\varepsilon + \sin\Delta_\odot\sin\varepsilon \\ -\cos\Delta_\odot\sin A_\odot\sin\varepsilon + \sin\Delta_\odot\cos\varepsilon \end{pmatrix} \tag{14}$$

which is another way of writing Eq. (6). We then obtain $\Lambda_\odot$ and $B_\odot$ for use later.

All of this is done separately for the three times and represents overhead.

D. Planetary Aberration

$\underline{R} = R\underline{\ell}(A, \Delta)$ is the <u>geometric</u>, spherical, equatorial location for the mean equator and equinox of date at some instant of interest (say 12 A.M.). However, because the speed of light c (in vacuo) is not infinite and the minor planet is a reasonable distance ($\sim$ 2 A.U.) away, the light reflected at 12 A.M. won't reach us for another $\sim 10^3$ seconds during which time the relative orientation of the Earth and the asteroid will have changed (at something less than 1"/min for most main belt asteroids) by $\lesssim$ 17". This is the planetary aberration and we must correct for it. Given the $\sim$ 1' accuracy in the position (cf. §§VA) we can afford a very simple form of correction. In particular I assume that the motion of the Earth and that of the asteroid is uniform and rectilinear in the time interval R/c. Then, if $\dot{A}$ and $\dot{\Delta}$ are the rates of change of A and Δ, the values of A and Δ corrected for planetary aberration are $A - \dot{A}R/c$ and $\Delta - \dot{\Delta}R/c$. Alternatively I could've predated the output time by R/c.

E. Other Effects

Other effects might include nutation, annual aberration (both circular and e-terms), diurnal parallax, diurnal aberration, astronomical refraction, and parallactic refraction. These can easily exceed 2' at a zenith distance of 60°. However, they are clearly not needed to point the telescope (cf. §VA) and have a negligible (0.03%) probability of causing us to not provide output for a minor planet at $Z = 60°01'$ which these effects (principally astronomical refraction) might have raised up to $Z = 59°59'$. They are also not needed in ASTID because the input to ASTID will be the output from the calibration software[8] PLC or SSC(SAO) at the ETS. These provide positions relative to the mean equator and equinox (uncorrected for diurnal parallax or planetary aberration) at the beginning of the current calendar year*. Therefore, if all of these small corrections were added into the ASTPT software, I'd just have to delete them to change ASTPT into ASTID.

F. Brightness

The most recent and authoritative summary of asteroid absolute B magnitudes, phase functions, and the opposition effect is in reference 21. ASTPT uses slightly older values which can result in a difference of up to $0\overset{m}{.}35$ (at quadrature due to phase effects; at most $0\overset{m}{.}15$ near opposition). The apparent, exo-atmospheric B magnitude for a minor planet r A.U. from the Sun, R A.U. from the Earth, and at phase angle f (and away from opposition) is

$$B(rR,f) = B(1, 0) + 5\log(rR) + Ff \tag{15}$$

where f is the phase angle [see Fig. 3 and Eq. (17)] and F (old) $= 0\overset{m}{.}023$/deg. F(new) $= 0\overset{m}{.}039$/deg. The quantity Ff is the

*This is a U.S. Air Force desire.

phase function in magnitudes (and this notation is not standard). Equation (15) is valid for $8° \lesssim f \lesssim 22°$ (quadrature). When the phase angle is near zero ($f = 0$ implies opposition) the asteroids brighten perceptibly faster than the linear form in Eq. (15) would indicate. This is known as the opposition effect and it is given by (old)

$$\begin{aligned} B(1,f) &= 0\overset{m}{.}188|f|^{0.545} + 8°F - 0\overset{m}{.}584 + B(1,0) \\ &= 0\overset{m}{.}188|f|^{0.545} - 0\overset{m}{.}400 + B(1,0) \end{aligned} \tag{16}$$

The new form is

$$\begin{aligned} B(1,f) &= 0\overset{m}{.}134|f|^{0.714} + 7°F(\text{new}) - 0\overset{m}{.}538 + B(1,0) \\ &= 0\overset{m}{.}134|f|^{0.714} - 0\overset{m}{.}265 + B(1,0) \end{aligned}$$

Equation (16) is used when $|f| \leq 8°$. Figure 3 implies

$$\cos f = (R^2 + r^2 - R_{\odot}^2)/(2Rr) \tag{17}$$

Atmospheric extinction is proportional to the air mass involved and the air mass is (roughly) proportional to the secant of the (topocentric, refracted) zenith distance. Ignoring several small effects (astronomical refraction, diurnal parallax, nutation, annual aberration, the deflection of the vertical, the angle of the vertical, and color effects), all of which sum to $< 0\overset{m}{.}1$, we can approximate the extinction, on any night we'll work, by

$$\varepsilon = 0\overset{m}{.}25 \sec Z$$

Z is computed from Eq. (18).

$$\cos Z = \sin\Delta\sin\phi + \cos\Delta\cos\phi\cos(\tau - A) \tag{18}$$

Finally then, our estimate (good to $\sim 0\overset{m}{.}1$) of the apparent S-20 magnitude of the minor planet is

$$m_{20} = B(rR,f) + O(|f|) + \varepsilon - 0\overset{m}{.}68 \tag{19}$$

where $O(|f|)$ is the opposition effect evaluated from Eq. (16) when appropriate and the constant represents the S-20/B color term from reference 22 using a B-V = $0\overset{m}{.}77$ (see §II). The scatter in B-V can introduce another $\pm\ 0\overset{m}{.}05$ error.

G. Visibility

For the purposes of ASTPT an asteroid is "visible" if and only if its orbital element set (epoch 1950.0, date of osculation) passes the user requested inclination and eccentricity tests, has a value of m_{20} (evaluated at midnight) from Eq. (19) that satisfies the user requested magnitude limits, and has a value of Z from Eq. (18) less than 60° (evaluated at midnight). If an asteroid passes all of these tests then the 6 P.M. and 6 A.M. positions are computed, the geocentric angular velocity computed at midnight from the three positions by differentiating a three-point Lagrange interpolation formula, the planetary aberration correction applied, the time to move

$7\overset{''}{.}5$ calculated, output prepared, and the requisite information stored for a potential sort.

To paraphrase the Explanatory Supplement to The Astronomical Ephemeris and the American Ephemeris And Nautical Almanac, even when the computations are not performed as discussed above or as in §VI, neither are they done very differently nor is any appreciable (at ± 1') error introduced.

VI. THE TRICKS

Clearly the computation of a spherical, equatorial, geocentric position of an asteroid for an arbitrary mean equator and equinox represents a fair amount of calculation. To make ASTPT and especially ASTID run as quickly as possible this should be avoided whenever feasible. My methods of doing this are given in subsection D below. A very simple way of saving CPU time is to run in single precision (21 bits ≈ 0".1 on my computer) instead of double precision (37 bits ≈ 1 μ arc sec). All overhead* is performed in double precision and then truncated. All other computations are performed in single precision.

A. Heliocentric Locations

The vector $\underset{\sim}{r}_o$ for midnight is calculated as outlined in §VA (i.e., rigorously). The 6 P.M. and 6 A.M. values are then computed differentially via

$$\underset{\sim}{r}_o(t + \Delta t) = \underset{\sim}{r}_o(t) + (d\underset{\sim}{r}_o(t)/dt)\Delta t \tag{20a}$$

where t = midnight, $\Delta t = \pm 6^h$, and, from Eqs. (1, 8)

$$\frac{d\underset{\sim}{r}_o(t)}{dt} = n[(\cos E)\underset{\sim}{B}_o - (\sin E)\underset{\sim}{A}_o]/(1 - e\cos E) \tag{20b}$$

*Overhead consists of the creation of the master asteroid file (e.g., $\underset{\sim}{A}_o$, $\underset{\sim}{B}_o$, n, etc.), the geocentric location of the Sun, the local mean sidereal time, the general precession matrix P, and the ecliptic latitude and longitude of the astronomical zenith.

where it's the 12 A.M. value of the eccentric anomaly that is used. The second-order error can scarcely exceed $0\rlap{.}''5$ for an object moving at 1"/min.

B. General Precession and Parallax

The vector $\underline{r}$ for midnight is rigorously computed from Eqs. (13) (i.e., $\underline{r} = P\underline{r}_o$ with the values for the equatorial precessional quantities evaluated at midnight). From Eq. (8) we see that this involves the computation of $P\underline{A}_o$ and $P\underline{B}_o$. If we don't adjust P for the $\pm\ 6^h$ and use Eqs. (20), then no additional matrix multiplications are required to obtain the 6 A.M. or 6 P.M. values of $\underline{r}$ relative to the mean equator and equinox of midnight. Since $m \approx 46\rlap{.}''1$/yr and $n \approx 20\rlap{.}''$/yr, the maximum error, from Eqs. (11, 12) is $< 0\rlap{.}''05$ for any place on the celestial sphere. And this is the greatest of all upper bounds.

As the location of the Sun is highly accurate and Fig. 3 is rigorous, the parallax (heliocentric-geocentric) correction is performed rigorously at the three times of interest. Moreover, rigorous parallax for ecliptic coordinates can be written as

$$\tan(\Lambda - \lambda) = \frac{\cos B_\odot \sin(\Lambda_\odot - \lambda)}{(r/R_\odot)\cos\beta + \cos B_\odot \cos(\Lambda_\odot - \lambda)} \tag{21a}$$

$$\tan(B - \beta) = \frac{\sin B_\odot \csc\gamma \sin(\gamma - \beta)}{(r/R_\odot) + \sin B_\odot \csc\gamma \cos(\gamma - \beta)} \tag{21b}$$

where

$$\tan\gamma = \tan B_{\odot}\cos[(\lambda - \Lambda)/2]\sec[\Lambda_{\odot} - (\lambda + \Lambda)/2] \tag{21c}$$

This will be used later (§VID). Note though, that since $|B_{\odot}| \leq 1''.2$ unless $\Lambda_{\odot} - (\lambda + \Lambda)/2 = \pm 90°$, $\gamma \simeq 0$ too.

C. Planetary Aberration

The only approximation made here, not already detailed in §VD, is to use the same planetary aberration correction at all three times of interest. This error is comparable to that made in the rectangular, heliocentric, 1950.0 locations because it depends on the relative acceleration of the Earth and the asteroid over the $\pm 6^h$.

D. Visibility

An asteroid must pass four levels of tests before its position is ever computed. Two more levels of tests are required after the position is available. These concern zenith distance and apparent magnitude (§VID6). Additional, preliminary zenith distance (§VID4) and apparent magnitude (§VID2) tests are also performed.

1. User Inclination and Eccentricity Limits

Obviously the quickest methods of elimination are to ensure that $i_\ell \leq i_o \leq i_u$ and $e_\ell \leq e \leq e_u$ and these are performed first.

2. User Apparent Magnitude Test (Preliminary)

For the huge majority of the asteroids in the main belt the perihelion opposition magnitude [m_δ; $r = a(1 - e) = q$, R = q - 1] is brighter than the mean opposition magnitude (r = a, R = a - 1) which is brighter than the aphelion opposition magnitude [r = a(1 + e), R = a(1 + e) - 1] which, in turn, is brighter than the mean quadrature magnitude [$m_{\sqcap}$; r = a, R = $(a^2 - 1)^{1/2}$, f = $\sin^{-1}(1/a)$]. Including extinction for one air mass these are (in the blue)

$$
\begin{aligned}
m_{☍} &= B(1,0) + O(o) + 5\log[q(q-1)] + 0^{m}.25 \\
m_{\square} &= B(1,0) + 5\log[a(a^2-1)^{1/2}] + F\sin^{-1}(1/a) + 0^{m}.25
\end{aligned}
\qquad (22)
$$

Therefore, if $m_{\sqcup} < m_b$ or $m_{☍} > m_f$, then the minor planet can be eliminated [when $m_{☍}$ and $m_{\sqcap}$ are corrected for the S-20/B color term as in Eq. (19)]. The value of the perihelion opposition magnitude and mean quadrature magnitudes, so adjusted, are on the master asteroid tape file and read in with the orbital element set, $\underset{\sim}{A}_o$, $\underset{\sim}{B}_o$, etc.

3. Right Hemisphere Test

Roughly half* of all of the asteroids are going to be in the wrong hemisphere of the celestial sphere at any given time. If they can be efficiently eliminated from consideration early then a great deal of computation will be saved. This test is designed to do just this. Consider Fig. 4. Only those minor

*This assumes, among other things, a uniform distribution of mean longitudes. This is not the case, primarily due to perturbations from Jupiter. There are noticeable peaks in the longitude of ascending node distribution function near $\Omega_{♃}$ and $\Omega_{♃} + 180°$. A similar, smaller effect, is present in the argument of perihelion.

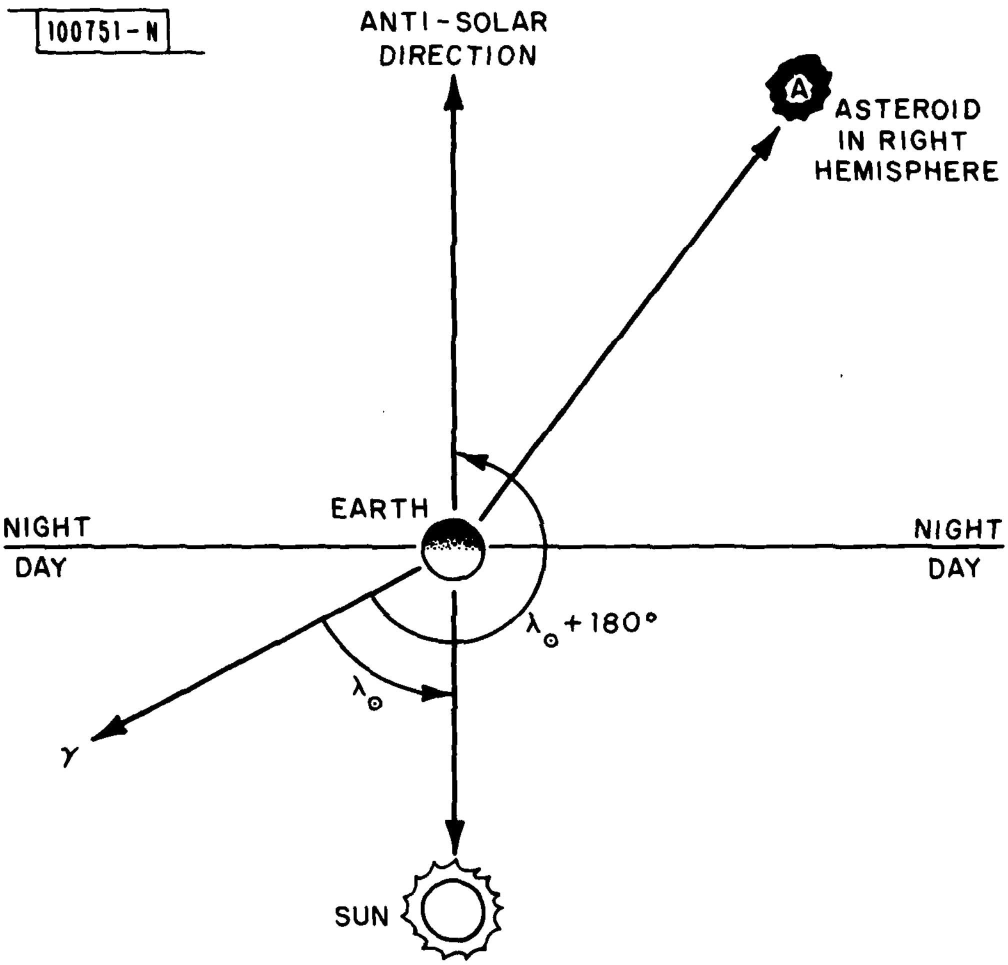

Fig. 4. Minor planets with geocentric ecliptical longitudes.

planets with geocentric ecliptic longitudes $\Lambda \varepsilon (\Lambda_\odot + 90°, \Lambda_\odot + 270°)$ are of interest. But it is λ_o we can get from the orbital element set, not Λ or even λ.

We start from

$$\lambda_o = \Omega_o + \tan^{-1}(\cos i_o \tan u_o) \tag{23}$$

where u_o is the true argument of latitude $= \omega_o + v$. (v is the true anomaly we didn't compute in §VA.) Since*, by and large, $e_o \leq 0.3$ and $i_o \leq 30°$ we can use

$$\lambda_o \simeq \lambda'_o = \Omega_o + \omega_o + M + 2e\sin M + (5e^2/4)\sin 2M \tag{24}$$

where M is the mean anomaly, the Taylor series of Eq. (23) about $i_o = 0$ has been used through first-order terms in i, and the Taylor series of Eqs. (1,3) about $e = 0$ have been used through second-order terms in e. Numerically†, the worst Eq. (24) is is $2\overset{\circ}{.}7 \pm 1\overset{\circ}{.}6$ averaged over $\omega_o = 0(15)360°$, $M = 0(15)360°$ for test values of $i_o = 0(5)30°$, $e = 0(0.05)0.30$. Not surprisingly this occurs for $i_o = 30°$ and $e = 0.30$. Dropping the quadratic term in e raises $2\overset{\circ}{.}7 \pm 1\overset{\circ}{.}6$ to $9\overset{\circ}{.}2 \pm 28\overset{\circ}{.}6$. Now that we've got a $\pm 5°$

---

*Compare with reference 17.

†These results refer to the mean value of $|\lambda_o - \lambda'_o|$ and its standard deviation about the mean, i.e., $\underset{\substack{\omega_o = 0(15)360° \\ M = 0(15)360°}}{\text{mean}} |\lambda_o - \lambda'_o|$ at a fixed i_o and e is computed and $2\overset{\circ}{.}7$ was the largest value in the i_o, e ranges.

approximation for λ_o we need to precess it to the equator and equinox of date. In terms of the quantities a, b, and c introduced in Eq. (9) general precession for spherical ecliptic coordinates is given by (to the second-order)

$$\lambda = \lambda_o + a - b\cos(\lambda_o + c)\tan\beta$$
$$\beta = \beta_o + b\sin(\lambda_o + c)$$

But $a \simeq 0^\circ\!.46$, $b \simeq 15''\!.5$ and since β is small (by hypothesis) we can ignore general precession completely in both λ and β (at the $\pm 5°$ level). Just to be safe the general precession in longitude has been kept in (it's overhead) so

$$\lambda \simeq \lambda' = \lambda_o' + a \simeq \lambda_o + a$$

To get Λ (or an approximation to it) we look at Eq. (21a) and realize that $B_\odot = 0$ (within $1''\!.2$). Note also that $R_\odot$ = 1 A.U. (within $e_\odot = 0.01675$). Therefore,

$$\tan(\Lambda - \lambda) = \frac{\sin(\Lambda_\odot - \lambda)}{(r/R_\odot)\cos\beta + \cos(\Lambda_\odot - \lambda)}$$

To at worst $1^\circ\!.2 \pm 1^\circ\!.5$ [for $(r/R_\odot)\cos\beta = 1.5(0.5)5.0$ A.U. and averaged over $\Lambda_\odot - \lambda = 0(15)360°$ as above, e.g., for the mean of $|\Lambda - \lambda|$] we can approximate this by

$$\Lambda - \lambda \simeq \Lambda' - \lambda' = \frac{\sin(\Lambda_\odot - \lambda')}{(r/R_\odot)\cos\beta + \cos(\Lambda_\odot - \lambda')}$$

$$- \left[\frac{\sin(\Lambda_\odot - \lambda')}{(r/R_\odot)\cos\beta + \cos(\Lambda_\odot - \lambda')}\right]^3 \Big/ 3 \qquad (25)$$

Finally, for $r\cos\beta$ we use $a(1 - e\cos M)$ which is accurate to 0.066 ± 0.047 in $(r/a)\cos\beta$ (averaged over ω_o, M; the worst here is for $i_o = 30°$, $e = 0$).

We now have an approximate ($\lesssim 5°$) value for Λ at the cost of sinM, cosM, $\sin(\Lambda_\odot - \lambda')$, and $\cos(\Lambda_\odot - \lambda')$. And none of these are wasted (cf. §§VID4, VID5). Using our approximate value for Λ we reject all minor planets not within 95° of $(\Lambda_\odot + 180°)\bmod(360°)$. If either $e > 0.3$ or $i_o > 30°$ then this computation is bypassed.

4. Above Horizon Test (Preliminary)

Only one-quarter of the celestial sphere is above altitude = 30°. Hence, if we can eliminate those minor planets below this (and do it cheaply), another large savings will be made. Of course, it won't be three-quarters because half of the celestial sphere has already been ruled out. I expect that about half of the remaining candidates will be eliminated here. To do this though we need to compute the minor planet's zenith distance. To use Eq. (18) for cosZ clearly involves knowledge of the equatorial position. Hence we need another method. This trick consists of computing cosZ in the ecliptic coordinate system.

If B_z, L_z are the spherical, geocentric, mean equator and equinox of date, ecliptic latitude and longitude of the astronomical zenith and B, Λ the corresponding coordinates for the asteroid, then

$$\cos Z = \underline{\ell}(\Lambda, B) \cdot \underline{\ell}(L_z, B_z) \tag{26}$$

Since Eq. (14) represents the general relationship between spherical ecliptic and spherical equatorial coordinates, and the declination of the astronomical zenith is ϕ while its right ascension is just τ,

$$\underline{\ell}(L_z, B_z) = \begin{pmatrix} \cos\phi\cos\tau \\ \cos\phi\sin\tau\cos\varepsilon + \sin\phi\sin\varepsilon \\ -\cos\phi\sin\tau\sin\varepsilon + \sin\phi\cos\varepsilon \end{pmatrix} \tag{27}$$

Note that this is exact and $\underline{\ell}(L_z, B_z)$ represents overhead.

The approximation for B is straightforward. We have, rigorously,

$$\beta_o = \sin^{-1}(\sin i_o \sin u_o) \tag{28}$$

whence

$$\beta_o \approx \beta_o' = i_o \sin(\omega_o + M + 2e\sin M) \tag{29}$$

never worse than 1°3 $\pm$ 1°0 [cf. the discussion following Eq. (24); again for $i_o \leq 30°$, $e \leq 0.3$ and this is the 30°, 0.3 value]. We already know that general precession is negligible, so, with this accuracy $\beta \simeq \beta_o'$. Parallax is also simple. From Eqs. (21), with $\sin B_\odot \csc\gamma \simeq B_\odot/\gamma \simeq \tan B_\odot/\tan\gamma$ $= \cos[\Lambda_\odot - (\lambda + \Lambda)/2]\sec[(\lambda - \Lambda)/2]$,

$$\tan(B - \beta) \simeq \frac{-\sin\beta}{(\gamma/B_\odot)(r/R_\odot) + \cos\beta}$$

because $\gamma \simeq 0$ unless $\Lambda_\odot - (\lambda + \Lambda)/2 = \pm 90°$. And if we neglect parallax for the moment, this is the same as $\Lambda_\odot - \Lambda = \pm 90°$ so we realize that the points of greatest trouble have already been declared uninteresting. Finally, then

$$B - \beta \simeq B' - \beta' = \frac{-\sin\beta'}{(\gamma/B_\odot)(r/R_\odot) + \cos\beta'} - \left[\frac{-\sin\beta'}{(\gamma/B_\odot)(r/R_\odot) + \cos\beta'}\right]^3 \Big/ 3 \tag{30}$$

with an accuracy of at worst 2°.2 $\pm$ 1°.4 [averaged over β' $= -90(10)90°$ for $(\gamma/B_\odot)(r/R_\odot) = -5(0.5)-1.5$]. Substituting for β' using Eq. (29) and using $r/a = 1 - e\cos M + (e^2/2)\cdot(1 - \cos 2M)$ (good to 0.0003 ± 0.0019 even at $e = 0.3$) completes the computation of B'. The secant of $(\lambda' - \Lambda')/2$ is computed from $1 + (\lambda' - \Lambda')^2/8$ since* $|\lambda - \Lambda| \lesssim 20°$. The quantity

---

*From Eq. (21a) with $B_\odot = 0$ $R_\odot = 1$ A.U. it follows that $|\tan(\Lambda - \lambda)| \leq (r^2\cos^2\beta - 1)^{-1/2}$ (this is rigorous). At $r\cos\beta = 2.7$ A.U. this implies $|\Lambda - \lambda| < 22°$.

$\cos[\Lambda_\odot - (\lambda' + \Lambda')/2] = \cos[\Lambda_\odot - \lambda' + (\lambda' - \Lambda')/2]$ is calculated as

$$\cos(\Lambda_\odot - \lambda')[1 - (\lambda' - \Lambda')^2/8] - \frac{(\lambda' - \Lambda')}{2} \sin(\Lambda_\odot - \lambda')$$

Therefore only the trigonometric function in Eq. (29) is needed.

We started by computing four trigonometric functions in the right hemisphere test. This is less work than just solving Kepler's equation (see below). Hence, if the minor planet can be eliminated on this basis a huge savings will result. Of those four trigonometric functions two are used in this test. And if the minor planet is eliminated from further consideration now, then a total of five trigonometric functions have been computed. This is still cheaper than solving Kepler's equation. The actual test used is that if $\cos Z$, computed from Eq. (26) using Eqs. (25, 30) for Λ and B is $< 1/3$ (which corresponds to the error in $\cos Z$ from the accumulation of all of the various approximates, i.e., at worst $3\overset{\circ}{.}9 \pm 2\overset{\circ}{.}1$ in Λ and $3\overset{\circ}{.}5 \pm 1\overset{\circ}{.}8$ in B) then the minor planet is rejected.

5. Kepler's Equation

At this point I'm out of tricks and the full midnight position must be computed. As discussed in §VA the first step is to compute the mean anomaly M (already done) and then solve Kepler's equation, Eq. (1). Four such methods have been tried over the $e = 0(0.05)0.30$, $M = 0(15)360°$ ranges. The fastest is Newton's method,

$$E_{new} = E_{old} - \frac{(E_{old} - e\sin E_{old} - M)}{1 - e\cos E_{old}}$$

if $|E_{new} - E_{old}|$ is small enough, then $E = E_{new}$ and terminate

otherwise $E_{old} = E_{new}$ and repeat

with the original $E_{old} = M + e\sin M$. On the average this requires 2.5 iterations. The second fastest is Newton's method with a starting guess of $E_{old} = M$ (3 iterations on average). But for this case the sine and cosine of M are needed, we already have these, and Newton's method starting with $E_{old} = M$ and the additional headstart of sinM, cosM is the fastest of all. Hence, when passing through the right hemisphere and zenith distance tests only a single trigonometric function, the one in Eq. (29), is "wasted".

6. The Rest

Any asteroid getting to the solution of Kepler's equation (and this automatically includes the few for which either $e > 0.3$ or $i_o > 30°$) has its spherical, equatorial, geocentric, mean equator and equinox of date location computed as outlined in §§VA, VB, VC, VE, VIA, and VIB. Then cosZ is calculated from Eq. (18). If it's $\leq 1/2$ the minor planet is rejected. If not, then m_{20} is calculated from Eq. (19)

and tested against m_b, m_f. If it passes this test, then the 6 P.M. and 6 A.M. locations are computed, the geocentric angular speed calculated $\{\dot{A}(12\ \text{A.M.}) = 2[A(6\ \text{A.M.}) - A(6\ \text{P.M.})]$, $\dot{A}$ per hour, etc.$\}$, the planetary aberration applied, the time to move 7".5 computed, the position angle and direction of the geocentric angular velocity obtained, output readied, and much of this stored if a sort has been requested.

E. ASTID Visibility

In this mode only asteroids within a few degrees of a particular geocentric ecliptic latitude and longitude are of interest. From the equatorial coordinates of the asteroid being observed we compute the corresponding ecliptic coordinates [by inverting Eq. (6) with appropriately accurate general precession and planetary aberration included; we started with a geocentric right ascension and declination for the mean equatorial equinox of 1980.0 (for 1980)]. Call these L*, B*. For each asteroid on file we calculate Λ' from Eq. (25) and reject it as a candidate for identification if $|\Lambda' - L^*| > 5°$. On the average this eliminates 35/36 = 97.2% of the entire catalog. If a minor planet passes this step we get B' as in Eq. (30) and then eliminate it if $|B' - B^*| > 5°$. This removes 170/180 of the remainder, leaving about 3 (plus the high e, i_o) for further consideration. Of course, the m_f test (§VID.2) is applied first and since m_{20} can be estimated at the telescope (to $\pm 1^m$) if the operator has input this value, it's used earlier too.

VII. ASTID

The ASTID visibility tricks given in §VIE are a natural outgrowth of those used in ASTPT. We can obtain a rough estimate of their relative speeds of execution as follows: Assume that the eccentricity and inclination limits are at their default values. If the right hemisphere test eliminates half of these and the preliminary above the horizon test eliminates half the remainder, then we have $\sim$ 550 left. In addition we have $\sim$ 50 high e or high i_o objects so ASTPT must fully process $\sim$ 600 minor planets. In the ASTID outlined above we have $\sim (1 - 35/36)(1 - 17/18)2200 + 50$ to process, or 53. Thus, assuming that the program overhead is negligible compared to the location computation, the relative speed should be $\sim$ 12. A bit more conservative estimate is the $\sim$ 10 quoted in the Introduction. This is still far too long ($\sim$ 6 seconds).

In particular, when ASTPT is run during the day, for that evening, we will save the midnight A, Δ, $\dot{A}$, and $\dot{\Delta}$ values calculated for all asteroids that were visible. Now, from the current telescope position and time (i.e., right ascension and declination) ASTID computes the corresponding asteroid position direction cosines using $A = A(12 \text{ A.M.}) + \dot{A}\Delta t$, etc. and we investigate the size of

$$\cos D = \underline{\ell}(A,\Delta) \cdot \underline{\ell}(A_T,\Delta_T)$$

where A,Δ are for a particular asteroid at this instant and

A_T, Δ_T are for the telescope position. D is the angular distance between the two points and we test for $\cos D < 1 - 2^{-20}$ or $D < 4\overset{s}{.}7$. This includes orbital element set errors, telescope errors, and computational errors (there are <u>no</u> errors in A, Δ due to the parallax, general precession, or other approximations used elsewhere in ASTPT). Clearly ASTID is now input-output bound (i.e., reading the $A, \Delta, \dot{A}, \dot{\Delta}$ file). The addition of this step to ASTPT will slow it down negligibly.

APPENDIX: User's Guide

ASTID is a real time program at the ETS and it is executed by pushing one of the buttons on the operating console (i.e., the one labeled ASTID). The execution of ASTPT is started by performing a console interrupt and then typing ASTPT//ACT,,TM. Sample sessions of the user interaction with ASTPT are shown in Tables A1 - A5.

Table A1 illustrates the full, normal method of choosing the default options. In this, and the other four tables, user inputs are underlined. All dialog appears on the line printer and on the CRT. When the code executes a top of form command it's been indicated by a dashed line here (to save space).

Table A2 illustrates the full, normal method of entry with several quantities being changed. The notation is fairly obvious ($m_b \rightarrow$ MB, $m_{20} \rightarrow$ MASTEROID, $i_o \rightarrow$ INCL, $\alpha \rightarrow$ RA, etc.)

Table A3 illustrates the form and nature of the error messages.

Table A4 illustrates an attempt at the quick method of entry. This failed and the user chose to return to the full, normal mode. To save space this is not given here.

Table A5 illustrates a successful quick mode session.

TABLE A1

```
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)

  AS IN 8 17 FOR AUGUST SEVENTEENTH

    IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE

2 5

YOU ENTERED 2 5

    IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN

      ANY INTEGER

-9

---------------------------------------------------------------

OUTPUT IS FOR 2 5 80 AT 6PM, 12AM, AND 6AM LOCAL

    IF YOU WANT QUICK INPUT ENTER A ZERO

55

DO YOU WISH TO IMPOSE MAGNITUDE LIMITS?

  THE DEFAULTS ARE 0 = MBRIGHT  .LE. MASTEROID .LE. MFAINT = 18.5

  TYPE A ONE TO ONLY CHANGE MBRIGHT
  TYPE A TWO TO ONLY CHANGE MFAINT
  TYPE A THREE TO CHANGE BOTH MBRIGHT AND MFAINT
  TYPE A FOUR TO CHANGE NEITHER MBRIGHT NOR MFAINT

4

YOU ENTERED 4

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN ANY

     INTEGER

4

---------------------------------------------------------------
```

THE MAGNITUDE LIMITS ARE   0.00 .LE. MASTEROID .LE. 18.50

DO YOU WISH TO IMPOSE INCLINATION LIMITS?

THE DEFAULTS ARE 0 = MIN INCL .LE. INCL .LE MAX INCL = 180

TYPE A ONE TO ONLY CHANGE MIN INCL
TYPE A TWO TO ONLY CHANGE MAX INCL
TYPE A THREE TO CHANGE BOTH MIN INCL AND MAX INCL
TYPE A FOUR TO CHANGE NEITHER MIN INCL NOR MAX INCL

4

YOU ENTERED 4

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN ANY

INTEGER

4

THE INCLINATION LIMITS ARE 0.00 .LE. INCL .LE. 180.00

DO YOU WISH TO IMPOSE ECCENTRICITY LIMITS?

THE DEFAULTS ARE 0 = MIN ECC .LE. ECC .LE MAX ECC = 1

TYPE A ONE TO ONLY CHANGE MIN ECC
TYPE A TWO TO ONLY CHANGE MAX ECC
TYPE A THREE TO CHANGE BOTH MIN ECC AND MAX ECC
TYPE A FOUR TO CHANGE NEITHER MIN ECC NOR MAX ECC

4

YOU ENTERED 4

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

ANY INTEGER

4

THE ECCENTRICITY LIMITS ARE 0.00 .LE. ECC .LE. 1.00

ENTER TAPE UNIT # -- 1 FOR MT1 OR 2 FOR MT2

1

YOU ENTERED 1

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN ANY INTEGER

1

TAPE SHOULD BE MOUNTED ON MT1

THE OUTPUT IS AUTOMATICALLY GIVEN BY INCREASING ASTEROID NUMBER

YOU MAY HAVE IT SORTED BY INCREASING RA, MAG, OR ANGULAR SPEED

THESE SORTS REQUIRE SOME EXECUTION TIME AND YOU HAVE EIGHT CHOICES

TYPE A ZERO FOR NO ADDITIONAL SORTING
TYPE A ONE FOR AN RA SORT
TYPE A TWO FOR A MAG SORT
TYPE A THREE FOR AN ANGULAR SPEED SORT
TYPE A FOUR FOR AN RA AND A MAG SORT
TYPE A FIVE FOR AN RA AND AN ANGULAR SPEED SORT
TYPE A SIX FOR A MAG AND AN ANGULAR SPEED SORT
TYPE A SEVEN FOR ALL THREE SORTS

0

YOU ENTERED 0

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN ANY INTEGER

1

YOU DESIRE NO ADDITIONAL SORTING

E X E C U T I O N   B E G I N S   N O W

TABLE A2

```
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)

 AS IN 8 17 FOR AUGUST SEVENTEENTH

  IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE

5 2

YOU ENTERED 5 2

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

     ANY INTEGER

88

-------------------------------------------------------------

OUTPUT IS FOR 5 2 80 AT 6PM, 12AM, AND 6AM LOCAL

    IF YOU WANT QUICK INPUT ENTER A ZERO

777

DO YOU WISH TO IMPOSE MAGNITUDE LIMITS?

  THE DEFAULTS ARE 0 = MBRIGHT .LE. MASTEROID .LE. MFAINT = 18.5

  TYPE A ONE TO ONLY CHANGE MBRIGHT
  TYPE A TWO TO ONLY CHANGE MFAINT
  TYPE A THREE TO CHANGE BOTH MBRIGHT AND MFAINT
  TYPE A FOUR TO CHANGE NEITHER MBRIGHT NOR MFAINT

1

YOU ENTERED 1

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

     ANY INTEGER

1

ENTER DESIRED MBRIGHT
```

12.56

YOU ENTERED 12.56

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN

ANY INTEGER

3

THE MAGNITUDE LIMITS ARE 12.56 .LE. MASTEROID .LE. 18.50

DO YOU WISH TO IMPOSE INCLINATION LIMITS?

THE DEFAULTS ARE 0 = MIN INCL .LE. INCL .LE MAX INCL = 180

TYPE A ONE TO ONLY CHANGE MIN INCL
TYPE A TWO TO ONLY CHANGE MAX INCL
TYPE A THREE TO CHANGE BOTH MIN INCL AND MAX INCL
TYPE A FOUR TO CHANGE NEITHER MIN INCL NOR MAX INCL

2

YOU ENTERED 2

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN

ANY INTEGER

5

ENTER DESIRED MAXIMUM INCLINATION IN DEGREES

23

YOU ENTERED 23.00

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN

ANY INTEGER

23

```
THE INCLINATION LIMITS ARE 0.00 .LE. INCL .LE. 23.00

DO YOU WISH TO IMPOSE ECCENTRICITY LIMITS?

  TYPE A ONE TO ONLY CHANGE MIN ECC
  TYPE A TWO TO ONLY CHANGE MAX ECC
  TYPE A THREE TO CHANGE BOTH MIN ECC AND MAX ECC
  TYPE A FOUR TO CHANGE NEITHER MIN ECC NOR MAX ECC

3

YOU ENTERED 3

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN ANY

     INTEGER

3

ENTER DESIRED MINIMUM ECCENTRICITY

0.01

YOU ENTERED 0.01

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

     ANY INTEGER

3

ENTER DESIRED MAXIMUM ECCENTRICITY

.99

YOU ENTERED 0.99

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN

     ANY INTEGER

7
----------------------------------------------------------------
```

```
THE ECCENTRICITY LIMITS ARE 0.01 .LE. ECC .LE. 0.99

ENTER TAPE UNIT # -- 1 FOR MT1 OR 2 FOR MT2

2

YOU ENTERED 2

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN

     ANY INTEGER

2
---------------------------------------------------------------

TAPE SHOULD BE MOUNTED ON MT2

THE OUTPUT IS AUTOMATICALLY GIVEN BY INCREASING ASTEROID NUMBER

YOU MAY HAVE IT SORTED BY INCREASING RA, MAG, OR ANGULAR SPEED

THESE SORTS REQUIRE SOME EXECUTION TIME AND YOU HAVE EIGHT CHOICES


 TYPE A ZERO FOR NO ADDITIONAL SORTING
 TYPE A ONE FOR AN RA SORT
 TYPE A TWO FOR A MAG SORT
 TYPE A THREE FOR AN ANGULAR SPEED SORT
 TYPE A FOUR FOR AN RA AND A MAG SORT
 TYPE A FIVE FOR AN RA AND AN ANGULAR SPEED SORT
 TYPE A SIX FOR A MAG AND AN ANGULAR SPEED SORT
 TYPE A SEVEN FOR ALL THREE SORTS

7

YOU ENTERED 7

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN

     ANY INTEGER

7
---------------------------------------------------------------

YOU DESIRE ALL THREE - THIS WILL TAKE AWHILE

   E X E C U T I O N   B E G I N S   N O W
```

TABLE A3

```
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)
 AS IN 8 17 FOR AUGUST SEVENTEENTH
  IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE
13 2
      AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)
 AS IN 8 17 FOR AUGUST SEVENTEENTH
  IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE
1 32
      AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)
 AS IN 8 17 FOR AUGUST SEVENTEENTH
  IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE
1 1
YOU ENTERED 1 1
   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN
     ANY INTEGER
0
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)
 AS IN 8 17 FOR AUGUST SEVENTEENTH
  IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE
2 5
YOU ENTERED 2 5
```

```
    IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO;  IF NOT THEN
      ANY INTEGER
666
------------------------------------------------------------------
OUTPUT IS FOR 2 5 80 AT 6PM, 12AM, AND 6AM LOCAL
   IF YOU WANT QUICK INPUT ENTER A ZERO
DD
     T R Y   A G A I N  -  B A D   R E A D
   IF YOU WANT QUICK INPUT ENTER A ZERO
6
DO YOU WISH TO IMPOSE MAGNITUDE LIMITS?
 THE DEFAULTS ARE 0 = MBRIGHT .LE. MASTEROID .LE. MFAINT = 18.5
 TYPE A ONE TO ONLY CHANGE MBRIGHT
 TYPE A TWO TO ONLY CHANGE MFAINT
 TYPE A THREE TO CHANGE BOTH MBRIGHT AND MFAINT
 TYPE A FOUR TO CHANGE NEITHER MBRIGHT NOR MFAINT
3
YOU ENTERED 3
   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN
     ANY INTEGER
3
ENTER DESIRED MBRIGHT
19
        AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE
ENTER DESIRED MBRIGHT
15.
```

```
YOU ENTERED 15.00

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN

     ANY INTEGER

2

ENTER DESIRED MFAINT

14.99

        AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE

ENTER DESIRED MFAINT

17.5

YOU ENTERED 17.50

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN

     ANY INTEGER

3
-----------------------------------------------------------------

THE MAGNITUDE LIMITS ARE 15.00 .LE. MASTEROID .LE. 17.50

DO YOU WISH TO IMPOSE INCLINATION LIMITS?

  THE DEFAULTS ARE 0 = MIN INCL .LE. INCL .LE MAX INCL = 180

  TYPE A ONE TO ONLY CHANGE MIN INCL
  TYPE A TWO TO ONLY CHANGE MAX INCL
  TYPE A THREE TO CHANGE BOTH MIN INCL AND MAX INCL
  TYPE A FOUR TO CHANGE NEITHER MIN INCL NOR MAX INCL

3

YOU ENTERED 3

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO:  IF NOT THEN

     ANY INTEGER

3
```

```
ENTER DESIRED MINIMUM INCLINATION IN DEGREES

-4

        AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE

ENTER DESIRED MINIMUM INCLINATION IN DEGREES

5

YOU ENTERED 5.00

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

     ANY INTEGER

5

ENTER DESIRED MAXIMUM INCLINATION IN DEGREES

15.67

YOU ENTERED 15.67

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

     ANY INTEGER

7

----------------------------------------------------------------

THE INCLINATION LIMITS ARE 5.00 .LE. INCL .LE. 15.67

DO YOU WISH TO IMPOSE ECCENTRICITY LIMITS?

  THE DEFAULTS ARE 0 = MIN ECC .LE. ECC .LE MAX ECC = 1

  TYPE A ONE TO ONLY CHANGE MIN ECC
  TYPE A TWO TO ONLY CHANGE MAX ECC
  TYPE A THREE TO CHANGE BOTH MIN ECC AND MAX ECC
  TYPE A FOUR TO CHANGE NEITHER MIN ECC NOR MAX ECC

3

YOU ENTERED 3

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN
     ANY INTEGER
```

```
3
ENTER DESIRED MINIMUM ECCENTRICITY
1.05
        AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE
ENTER DESIRED MINIMUM ECCENTRICITY
.5
YOU ENTERED 0.50
   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN
     ANY INTEGER
8
ENTER DESIRED MAXIMUM ECCENTRICITY
.3
        AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE
ENTER DESIRED MAXIMUM ECCENTRICITY
0.51
YOU ENTERED 0.51
   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN
     ANY INTEGER
5
---------------------------------------------------------------
THE ECCENTRICITY LIMITS ARE 0.50 .LE. ECC .LE. 0.51
ENTER TAPE UNIT # -- 1 FOR MT1 OR 2 FOR MT2
3
        AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE
ENTER TAPE UNIT # -- 1 FOR MT1 OR 2 FOR MT2
```

-9

AT LEAST ONE INPUT OUT OF BOUNDS - BE REASONABLE

ENTER TAPE UNIT # -- 1 FOR MT1 OR 2 FOR MT2

2

YOU ENTERED 2

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN

ANY INTEGER

2

TAPE SHOULD BE MOUNTED ON MT2

THE OUTPUT IS AUTOMATICALLY GIVEN BY INCREASING ASTEROID NUMBER

YOU MAY HAVE IT SORTED BY INCREASING RA, MAG, OR ANGULAR SPEED

THESE SORTS REQUIRE SOME EXECUTION TIME AND YOU HAVE EIGHT CHOICES

TYPE A ZERO FOR NO ADDITIONAL SORTING
TYPE A ONE FOR AN RA SORT
TYPE A TWO FOR A MAG SORT
TYPE A THREE FOR AN ANGULAR SPEED SORT
TYPE A FOUR FOR AN RA AND A MAG SORT
TYPE A FIVE FOR AN RA AND AN ANGULAR SPEED SORT
TYPE A SIX FOR A MAG AND AN ANGULAR SPEED SORT
TYPE A SEVEN FOR ALL THREE SORTS

5

YOU ENTERED 5

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN

ANY INTEGER

5

YOU DESIRE A RIGHT ASCENSION AND AN ANGULAR VELOCITY SORT

E X E C U T I O N   B E G I N S   N O W

TABLE A4

```
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)

  AS IN 8 17 FOR AUGUST SEVENTEENTH

    IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE

2 5

YOU ENTERED 2 5

   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

     ANY INTEGER

2

OUTPUT IS FOR 2 5 80 AT 6PM, 12AM, AND 6AM LOCAL

   IF YOU WANT QUICK INPUT ENTER A ZERO

0

   ENTER MB,MF,IL,IU,EL,EU,TAPE UNIT #

15.5 18 0 14 0 .23 99

   YOU GOOFED IT UP

       AT LEAST ON INPUT OUT OF BOUNDS - BE REASONABLE

IF YOU'D RATHER DO IT THE LONG WAY TYPE A ZERO

 OTHERWISE TYPE AN INTEGER

0

DO YOU WISH TO IMPOSE MAGNITUDE LIMITS?

   THE DEFAULTS ARE 0 = MBRIGHT .LE. MASTEROID .LE. MFAINT = 18.5

   TYPE A ONE TO ONLY CHANGE MBRIGHT
   TYPE A TWO TO ONLY CHANGE MFAINT
   TYPE A THREE TO CHANGE BOTH MBRIGHT AND MFAINT
   TYPE A FOUR TO CHANGE NEITHER MBRIGHT NOR MFAINT

4
```

```
YOU ENTERED 4
   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN
     ANY INTEGER
```

<u>etc.</u>

TABLE A5

```
ENTER THE MONTH AND DAY OF INTEREST (PROGRAM ASTPT 3/80)
  AS IN 8 17 FOR AUGUST SEVENTEENTH
    IT IS ASSUMED THAT THE YEAR IS THE CURRENT ONE
2 5
YOU ENTERED 2 5
   IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN
     ANY INTEGER
2
-------------------------------------------------------------
OUTPUT IS FOR 2 5 80 AT 6PM, 12AM, AND 6AM LOCAL
   IF YOU WANT QUICK INPUT ENTER A ZERO
0
   ENTER MB,MF,IL,IU,EL,EU,TAPE UNIT #
15.5 18 0 14 0.23 1
THE MAGNITUDE LIMITS ARE 15.50 .LE. MASTEROID .LE. 18.00
THE INCLINATION LIMITS ARE 0.00 .LE. INCL .LE. 14.00
THE ECCENTRICITY LIMITS ARE 0.00 .LE. ECC .LE. 0.23
TAPE SHOULD BE MOUNTED ON MT1
    IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN
      ANY INTEGER
0
    ENTER MB,MF,IL,IU,EL,EU,TAPE UNIT #
15.5 18. 0. 14. 0. 0.23 2
```

```
THE MAGNITUDE LIMITS ARE 15.50 .LE. MASTEROID .LE. 18.00

THE INCLINATION LIMITS ARE 0.00 .LE. INCL .LE. 14.00

THE ECCENTRICITY LIMITS ARE 0.00 .LE. ECC .LE. 0.23

TAPE SHOULD BE MOUNTED ON MT2

    IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

      ANY INTEGER

kk

     T R Y   A G A I N  -  B A D   R E A D

    ENTER MB,MF,IL,IU,EL,EU,TAPE UNIT #

15.5  18.  0.  14.  0.  0.23  2

THE MAGNITUDE LIMITS ARE 15.50 .LE. MASTEROID .LE. 18.00

THE INCLINATION LIMITS ARE 0.00 .LE. INCL .LE. 14.00

THE ECCENTRICITY LIMITS ARE 0.00 .LE. ECC .LE. 0.23

TAPE SHOULD BE MOUNTED ON MT2

    IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO: IF NOT THEN

      ANY INTEGER

3

THE OUTPUT IS AUTOMATICALLY GIVEN BY INCREASING ASTEROID NUMBER

YOU MAY HAVE IT SORTED BY INCREASING RA, MAG, OR ANGULAR SPEED

THESE SORTS REQUIRE SOME EXECUTION TIME AND YOU HAVE EIGHT CHOICES

  TYPE A ZERO FOR NO ADDITIONAL SORTING
  TYPE A ONE FOR AN RA SORT
  TYPE A TWO FOR A MAG SORT
  TYPE A THREE FOR AN ANGULAR SPEED SORT
  TYPE A FOUR FOR AN RA AND A MAG SORT
  TYPE A FIVE FOR AN RA AND AN ANGULAR SPEED SORT
  TYPE A SIX FOR A MAG AND AN ANGULAR SPEED SORT
  TYPE A SEVEN FOR ALL THREE SORTS
```

6

YOU ENTERED 6

IF YOU WISH TO CHANGE THIS ENTRY TYPE A ZERO; IF NOT THEN ANY INTEGER

6

YOU DESIRE AN APPARENT MAGNITUDE AND AN ANGULAR VELOCITY SORT

E X E C U T I O N   B E G I N S   N O W

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This Note discusses the design of software to be used for the planning of minor planet observations and the identification of a particular asteroid when it is observed. The large number of cataloged asteroids (~2200) has required that the software be optimal with respect to execution speed. This is accomplished by using an approximate geocentric ecliptic position to eliminate the minor planet from further consideration. In particular, using the type of analysis applicable to near-stationary artificial satellites, an approximate geocentric ecliptic latitude and longitude are obtained. The accuracy is (for $e \leqslant 0.3$, $i \leqslant 30°$) $3^{\circ}\!.9 \pm 2^{\circ}\!.1$ in geocentric ecliptic longitude and $3^{\circ}\!.5 \pm 1^{\circ}\!.8$ in geocentric ecliptic latitude. With these values we can eliminate approximately half of all asteroids. Half of the remainder are then eliminated because they will be below the observer's horizon. Here the asteroid's zenith distance is computed in the ecliptic coordinate system. The user's interaction with the software, complete documentation of the calculations, a user's guide, sample outputs, and the rationale of observing asteroids are also discussed.

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